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Reinspecting and offsetting lifecycle carbon with advanced materials in buildings for smart cities

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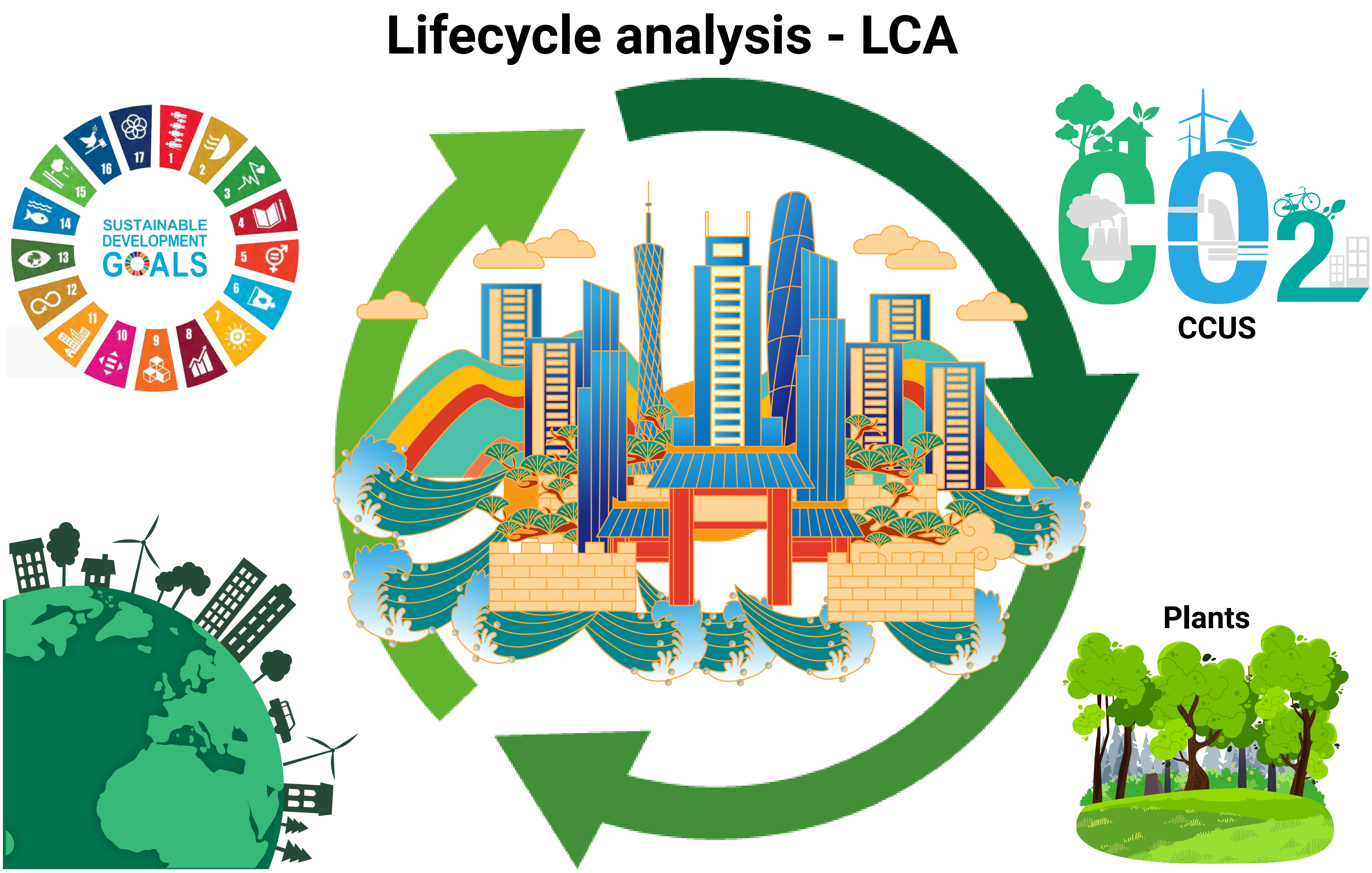
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- A cross-scale material-component-system framework underpins smart city decarbonization; revised LCA integrating carbon elimination and offsetting is required for quantitative carbon governance guidance.
- This work establishes a multi-scale nano-to-macro framework to offset building lifecycle carbon via energy transition, renewable systems, multi-energy storage and optimized building design.
- It updates the LCA methodology by incorporating CCS and afforestation carbon sinks, quantifying the function, mechanism and priority of diverse carbon neutralization strategies.
- The study identifies key carbon reduction bottlenecks and delivers targeted roadmaps, industrial initiatives and policy tools for China's building and energy chains to achieve 2060 carbon neutrality.

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A cross-scale 'material-component-system' framework is essential for climate change adaption, zero-carbon and Sustainable Development Goals (SDGs) of smart cities, whereas reinspecting lifecycle analysis (LCA) approach with carbon emission elimination and off-setting is highly necessary to provide stage-based quantifiable guidelines and initiatives. In this study, offsetting lifecycle carbon emissions in buildings was conducted through an innovative nano/micro/meso/macro-scale framework with cross-disciplinary mechanisms, such as electrification/hydrogenation transitions, consistent carbon database/standardization, passive/active designs, decentralised renewable unit, hybrid thermal-electrical-gas storages, advanced energy conversion and management, among others. Afterward, a reinspection of LCA approach is proposed with advanced carbon elimination and off-setting strategies (e.g., carbon capture and storage, photosynthesis conversion through tree planting and afforestation). Fundamental roles, underlying mechanisms and priority sequence of each strategy in carbon-neutrality are specifically quantified, together with bottlenecks and challenges. Finally, a roadmap, and initiatives and policy actions are provided in the building sectors and the entire energy supply chain in China, with carbon-positive and carbon-negative strategies for carbon neutrality in China by 2060.

INTRODUCTION

Worsening environmental conditions and contradictions between daily increased energy consumptions and intensified energy shortage call for an urgent transition to carbon neutrality. Carbon-neutral district energy communities with cleaner power production have been regarded as one of the most crucial and critical tasks follow-up steps toward carbon neutrality over past decades. For example, the president of the People's Republic of China has announced a dual-carbon reduction policy with goals for reaching the carbon emission peak before 2030, and realizing carbon neutrality by 2060.[1] To realise carbon neutrality, cross-disciplinary research, cutting-edge technologies for high-efficient and high-quality production in industry, concrete supports from local government and collaborative efforts are necessary from different sectors, such as district designers, energy planners, decision makers, etc. Assessing the lifecycle carbon footprint is of high importance in this context involving setting system boundaries, defining the scope of calculation carbon emissions and units of greenhouse gas emissions and methodologies.[2] Efforts have been made to reduce lifecycle green-house gas (GHG) emissions e.g. in urban buildings,[3] bamboo-structure building envelopes[4] and building materials.[5]

Electrification and hydrogenation in district energy systems play significant roles in energy paradigm transitions towards the carbon-neutral district energy community. For the energy paradigm transition following the low-carbon pathway, carbon reduction strategies include energy efficiency improvement, electrification of energy services, and carbon mitigation strategies, such as nuclear, new renewables, carbon capture and storage (CCS), and advanced biofuels.[6] Electrification in the end-use side can lead to 20% reduction in greenhouse gas (GHG) emission.[7] Shea et al.[8] conducted lifecycle cost analysis of a carbon-neutral campus, aiming at a transition towards a fully-electrified and renewable energy powered system. Their results show that due to reduced CO_2 emissions, electric vehicle fleet, geothermal heat pumps and off-site renewables savings of US$ 2, US$ 15.5, and US$ 1.7 million were achieved, respectively. In the EU and UK, realisation of 55% GHG emission reduction by 2030 requires increasing solar PV capacity to 455–605 GW. Nowadays, hydrogenation in district energy systems, i.e., hydrogen production and use, has attracted increased interest due to clean emissions (water) and high energy density (the calorific value of combustion of hydrogen is 1.43×10^8 J/kg, which is triple to gasoline). Furthermore, electrification of energy systems provides opportunities for renewable self-sufficiency improvement with multi-directional energy interactions. Zheng et al.[9] integrated renewable energy with electric vehicle charging infrastructure in China. The proposed strategy can enhance accessibility and achieve carbon abatement. Dan et al.[10] developed a city information models for optimal EV charging and energy-resilient renaissance, consisting of rooftop PVs, a community, battery storage, and power grid.

Embodied emissions in building materials and associated construction activities are full of challenges to be quantified due to the lack of consistent databases for multi-diversified materials, uncertainty in thermo-physical building materials, etc. In order to cover these gaps, researchers try to develop normalized carbon emissions for standardization. Chastas et al.[11] normalized carbon emissions in the building for further standardization in lifecycle analysis (LCA). Their results showed that the embodied carbon emissions account for 9%-22% of conventional, 32%- 38% of passive, and 21%-57% of low-energy buildings. In terms of the quantification of embodied emissions, Dixit[12] systematically reviewed the calculation approach for lifecycle recurrent embodied energy. They indicate that standardized database and calculation methods with probabilistic models based on past data can improve uncertainty quantification, with respect to geographic locations with different environmental qualities. Considering parameter uncertainties and their impact on embodied carbon emissions, researchers focused on uncertainty calculation models and CO_2 emission prediction models. Dixit[13] comprehensively reviewed modelling techniques for quantifications on initial and life cycle embodied energy, and highlighted the necessity for parameter standardization with uncertainty calculation models. Furthermore, with respect to the uncertainty of embodied carbon emissions, Robati et al.[14] adopted a random sampling approach to quantify the uncertainty of embodied carbon emissions following Monte Carlo simulations. The uncertainty analysis indicates that the total embodied CO_2 emission of a building is between 2951 to 5254 tCO_2-e. In order to reduce the embodied carbon emissions, researchers are mainly focusing on optimum sustainable design models,[15] pre-defined strategies,[16] data-driven models[17] for efficient and accurate prediction, and so on. Original material preparation and intelligent robot construction are emerging and promising techniques for the reduction in embodied emissions.

As one of the most effective strategies for carbon reduction, energy-efficient buildings with passive and active design strategies are critical to reduce the energy demand of energy districts, so as to reduce stress on the power grid and traditional fossil fuel-based power plants. Passive, active, and hybrid strategies have been employed, with respect to high-efficient utilization of natural sources and low-energy demands. Passive strategies for utilization of natural heating/cooling sources mainly include natural ventilation, diurnal and

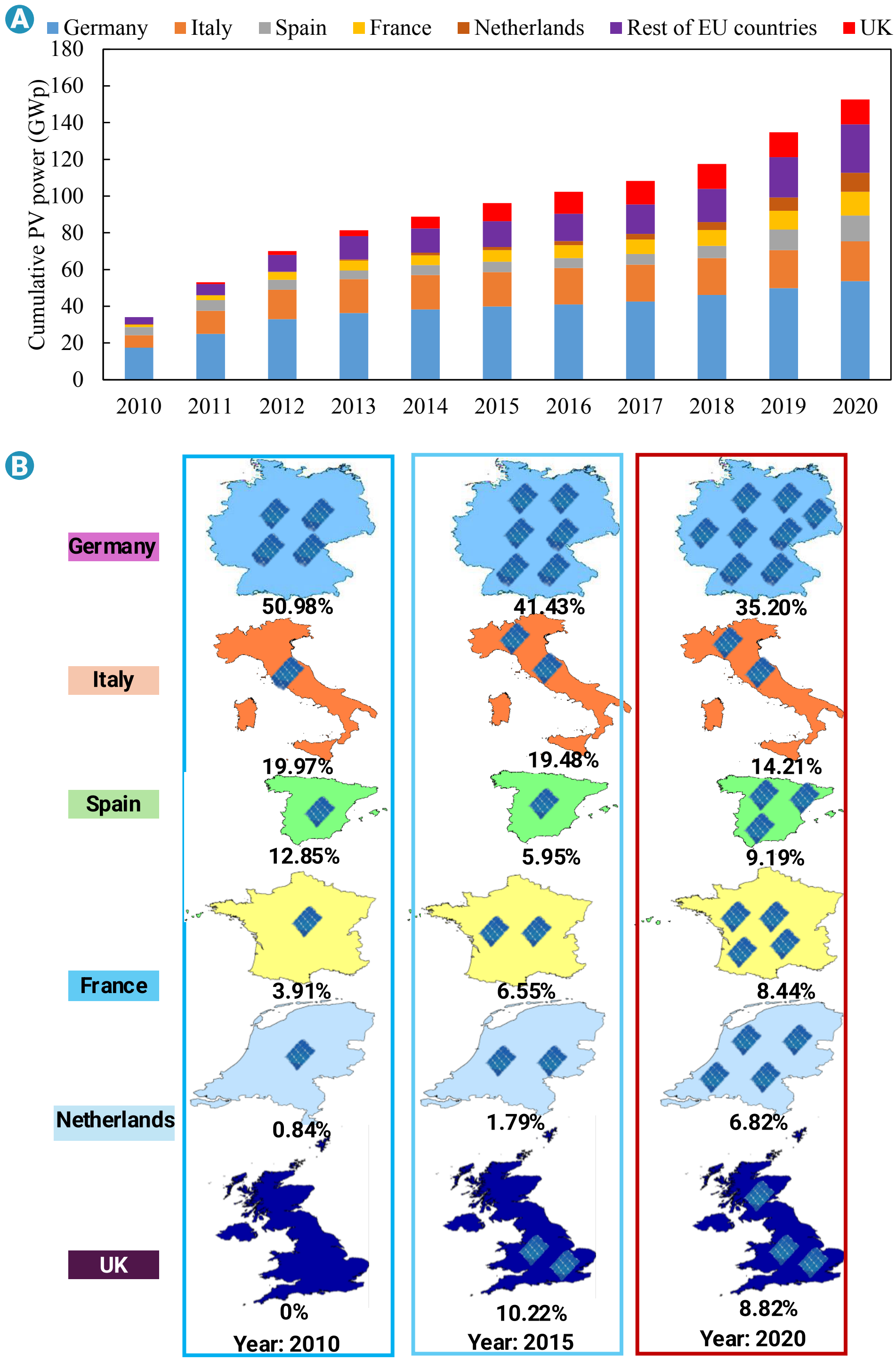

Figure 1. Grid-connected PV capacity in EU and the United Kingdom by 2020:[24] (A) cumulative PV power; (B) PV power proportion for each country in 2010, 2015 and 2020.

In addition to demand-side management, clean energy supply also plays a significant role for low-carbon district transitions. Renewable energy planning for cleaner power production is another powerful strategy for district carbon reduction. To smartly cover the peak demand, Waite and Modi[22] indicated that fossil fuels at only 3% of total American heating energy could avoid the peak electricity demands, providing decarbonization pathways for heating systems. Chen et al.[23] studied the energy flexibility of thermal power plants with intermittent renewable electricity. By dynamically balancing the load for renewable integration, the reduced magnitude in total emission cost can be accurately quantified. Compared to renewable deployment levels in EU and UK, China is currently undergoing rapid renewable installations and the increasing magnitude can be comparable or even more obvious than that in EU and UK. Grid-connected PV capacity in EU and the United Kingdom is shown in Figure 1. Renewable systems mainly include building-integrated photovoltaics (BIPVs) (suitable in highly densified metropolitans due to the space saving), floating PVs, and off-shore wind turbines. Jiang[27] systematically reviewed technical installation of off-shore wind turbines. The review provides guidelines on the widespread application of off-shore wind turbine systems. Chen et al.[23] studied the low-carbon pathway transition with the penetration of increased renewable energy generation. Contrary to the traditional power plant only serving energy demands, the traditional power plants need to simultaneously incorporate both energy demand and renewable energy generation, leading to the flexible operation characteristics.

Due to the spatiotemporal mismatch between energy demands and clean energy supplies, advanced energy conversion and energy management systems play essential roles in the energy transition towards carbon-neutrality. Such strategies can be mainly classified into so-called sector coupling, or power-to-X conversion, thermal and electrical storage-based

nocturnal sky radiative cooling. Meanwhile, active strategies mainly include smart appliances, smart heating, ventilation and air-conditioning (HVAC) controls, and demand-side management. In addition, energy-flexible buildings can enhance the grid resilience and improve the power supply reliability of intermittent renewable energy. The main functions of energy flexible buildings include immediate response and sufficient reaction to building energy demands by avoiding excessive production, increasing the stability of energy networks, and minimising energy congestion.[18] Approaches for energy flexibility mainly include flexible energy conversions [18], hybrid energy storages,[19] demand-side management,[20] and advanced controls.[21] Roles of energy flexible buildings in the carbon-neutrality transition include the grid-responsive support, replacement of traditional fossil fuel-based power plants with renewable energy, self-sufficiency with low reliance on backup systems, such as diesel engines, and so on.

management, synergistic operation of multi-energy networks (e.g., cooling, heating and power grids, carbon and gas/hydrogen networks) for power supply reliability, and district energy sharing. Power-to-X conversions enhance renewable energy penetration and load coverage,[18,28] operational cost saving,[28] and conversion of carbon dioxide to synthetic methane.[29] The main functions of energy storage include waste heat recovery,[30] reduction in energy demand,[31] energy costs,[32] and GHG emissions.[33] Synergistic grids' interaction can improve the system response time with direct energy forms and avoid exergy destruction in the energy conversion process. Furthermore, the district energy systems with a series of integrated subsystems, such as plug-in electric vehicles and interactive energy sharing with the mobile energy storage, can overcome the spatiotemporal intermittence of renewable power supply and exploit the abundant solar-wind resources for spatiotemporal energy migration. In other words, the energy-densified central power generation systems can be moved towards the suburbs, and the integrated transportation systems can carry the energy to the city center during the daily commuting process. Carbon capture and storage (CCS) as a carbon offsetting strategy could lead to carbon-negative effects. Babin et al.[34] studied the potentials of CCS when being designed as a carbon-negative energy source, for the carbon-neutrality transition. Results showed that strong policy support is necessary to address the concerns, such as food security, land use, water use, and application feasibility.

Over the past several decades, significant efforts have been made for the carbon-neutrality transition, from perspectives of energy forms transition towards electrification and hydrogenation,[35] embodied emissions with consistent database and parameter uncertainty,[36] novel passive and active strategies for energy-efficient buildings,[37] district renewable energy planning, energy conversion, and advanced energy management.[38] However, a systematic and comprehensive review has rarely been conducted, in terms of carbon elimination and off-setting strategies during the lifecycle process (i.e., raw materials preparation and prefabricated components, transportation, building design and construction, building energy system operation, and waste recycling). Furthermore, the roles and underlying mechanisms of each strategy in the carbon-neutrality transition have seldom been quantified. The bottlenecks and challenges in techniques have not clearly been identified. A systematic literature review on lifecycle-based carbon-neutrality transition is highly necessary to report the recent progress, identify challenges, illuminate future direction, and call for multidisciplinary and cross-disciplinary collaboration with joint efforts.

In this study, a comprehensive literature review was done on carbon elimination and off-setting strategies with respect to lifecycle processes, i.e., raw materials preparation and prefabricated components, transportation, building design and construction, building energy system operation, and waste recycling. The originality and novelty are summarised below:

1) A clear roadmap is provided for lifecycle carbon-neutrality transition, involving energy-efficient buildings, energy planning on renewable systems and hybrid thermal-electrical-gas energy storages, advanced energy conversion and management strategies.

2) This study holistically reviews and proposes a consistent database with uncertainty and standardization, software and tools for embodied carbon emission calculation, and strategies for reduction in lifecycle carbon emission. Furthermore, instead of unilaterally focusing either on embodied carbon emission in raw materials preparation, design and construction processes or on the system operating process, a novel lifecycle reinspecting approach is proposed with classifications on carbon-positive and carbon-negative strategies.

3) Current status, challenges, and outlook are clarified to call for cross-disciplinary research, cutting-edge technologies in the industry, concrete support from local governments on aspects of electrification and hydrogenation of multi-energy systems, energy-efficient buildings with energy flexibility, smart energy controls, and energy boundary for carbon neutrality.

This review is divided into six main sections. The first section reviews different types of energy paradigms from both operational and lifecycle perspectives, in terms of concept definition and global projects. In the second section, approaches for embodied carbon emission in building energy districts are studied from perspectives of uncertainty and standardization, software and tools in embodied carbon emission calculation, and strategies for reduction in lifecycle carbon emission. In the third section, energy-efficient buildings with passive, active, and hybrid strategies have been systematically reviewed, making preparations for the zero-energy or zero-emission district community. In the fourth section, cleaner power productions have been studied to replace the traditional fossil fuel-based power plants, with respect to BIPVs, floating PV farms, onshore/off-shore wind turbines. In the fifth section, efforts for energy conversion and management strategies towards the carbon-neutrality transition have been presented, including power-to-X conversions, thermal and electrical storage-based management, synergistic operation on multi-energy networks (e.g., cooling, heating and power grids, carbon and hydrogen networks) for power complementary and supply reliability, and district energy sharing. Last but not the least, outlook and recommendations are clarified from standpoints of electrification and hydrogenation of multi-energy systems, energy-efficient buildings with energy flexibility, smart energy controls, and energy boundaries for carbon neutrality.

An overview is shown in Figure 2 for the lifecycle-based techno-economic-environmental performance of district energy systems involving five phases, i.e., raw materials preparation and prefabricated components, transportation, building design and construction, building energy system operation, and waste recycling. During the stage of the raw materials preparation and prefabricated components embodied emission in building materials will have negative impacts on environmental performance. Other sources with negative impacts on environmental performance include embodied emission in renewable systems, operational emission from building services systems. In the carbon-neutral district energy community, the accumulated emission can be neutralized or offset by clean energy from renewable systems and recycled materials for decarbonisation. From the perspective of annual economic performance, associated costs include grid import/export cost, total energy cost, cost savings, and so on. Indicators for lifecycle performance analysis mainly include net direct energy consumption, discounted payback time, net present value (including initial investment cost, operational cost saving, operation, maintenance, replacement and residual cost, interest rate & inflation), and lifecycle environmental emission. Throughout the lifecycle carbon emission of buildings, as shown in Figure 2B, raw materials, maintenance & replacement and operation account for 16%, 15%, and 66% carbon emission[25]. In the raw materials, the maximum proportion of carbon emission is from reinforced concrete at 49.6%. In the operation and maintenance stage, the maximum proportion of carbon emissions of HVAC is 53.3%. In 2018, carbon emission was 15.51, 0.95 and 21.12 t $CO_{2,eq}$ in building sectors. Effective strategies are quite necessary to offset carbon emission and mitigate global warming.

An overall framework of the research methodology is shown in Figure 3 for carbon-neutrality transition of energy districts. Based on the overview on lifecycle-based carbon emissions of district energy systems, an overall framework for research methodology is introduced in Figure 3 to realise the carbon-neutral district energy community, including embodied carbon emission, energy-efficient buildings, renewable system planning, energy conversion and management, techno-economic-environmental objectives and multi-criteria decision-making. The embodied carbon emission includes uncertainty and standardization in embodied carbon emission, lifecycle carbon emission calculation, and strategies for reduction in embodied carbon emission. A systematic review on energy-efficient strategies was conducted including passive design strategy (e.g., nocturnal sky radiative cooling, Natural ventilative cooling, and passive storage), active design strategy (e.g., smart appliances, smart HVAC controls, and demand-side management), and hybrid design strategy. In addition to energy efficiency improvement from the demand-side, clean energy supply has also been investigated. To achieve carbon offsetting by replacing the traditional fossil fuel-based power plants, renewable systems planning strategies have been reviewed, including BIPVs, floating PV farms, and onshore/off-shore wind turbines. To mitigate the spatiotemporal mismatch between clean energy supplies and energy demands, various energy storages have been studied and discussed. The roles of thermal, electrical, and hydrogen energy storages in the carbon-neutrality transformation were studied with a specific focus on the carbon footprint of carbon emission factor. Based on the district energy demand and clean power supply, advanced energy conversion and management strategies are reviewed from perspectives of power-to-X conversions, storage-based management, synergistic operation on hybrid grids, and district energy sharing. Techno-economic-environmental objectives have been reviewed including annual (such as self-consumption, renewable penetration, grid shifted ratio and renewable shifted ratio) and lifecycle performances (such as discounted payback time, lifecycle emission, and net present value). To reach the trade-off solutions among the conflicting criteria, multi-objective optimisations were adopted to generate a Pareto-front. A multi-criteria decision-making approach with the incorporation of stakeholder priorities was adopted to select the 'best of the best' solution, to satisfy the requirement of different stakeholders.

MATERIALS AND METHODOLOGY

Negative, net-zero, and positive energy districts

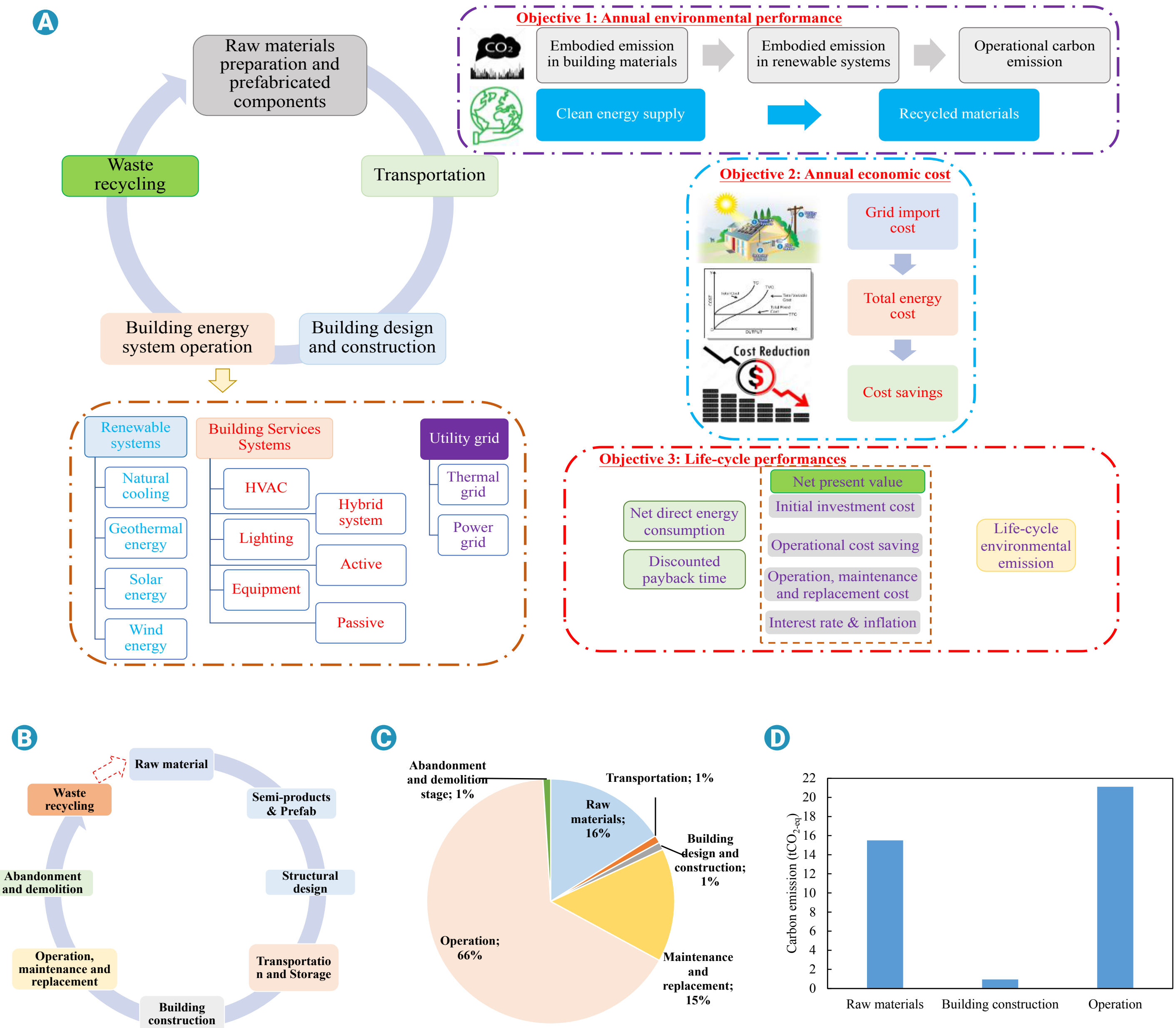

Figure 2. An overview of the lifecycle-based techno-economic-environmental performance of district energy systems (A) multi-criteria performance; (B) lifecycle carbon emission;[26] (C) proportion of carbon emission distribution in different stages; (D) amount of carbon emission in China 2018.

This review is based on keywords following a bibliometric approach in literature using the logics such as passive technologies, active technologies, hybrid strategies for energy-efficient buildings, 'source-grid-load-storage' planning, energy conversion and management strategies. Afterwards, considering the sustainable and smart cities with district buildings, negative, net-zero, and positive energy districts are included from concept definition and mechanism to embodied carbon emissions. The research scope and boundaries of this paper lie in energy-efficient buildings and building districts in sustainable and smart cities.

Concept definition and mechanism on energy paradigm transition. Figure 4 illustrates the definition of negative, net-zero and positive energy districts, together with carbon-negative, carbon-neutral and carbon-positive districts. In respect to the net-zero energy district, different conception definitions can be noticed, depending on the energy system boundary. During the operational period, as shown in Figure 4A, the net-zero energy district refers to the total renewable generation equal to the total district energy demand. By adopting energy-efficient strategies (such as building insulation, smart indoor setpoint temperature, internal shading, etc.), the district energy demand will move from the original point 1 towards point 2. After designing renewable systems until the total power generation equals the district energy demand, the energy district can become the net-zero energy, as indicated by point 3. Carbon neutrality refers to achieving net-zero carbon dioxide emissions through carbon offsetting or elimination strategies. The carbon positive refers to that the amount of CO_2 emissions removed from the environment is lower than the amount of CO_2 emissions released into the environment. The carbon-negative refers to that the amount of CO_2 emissions removed from the environment is higher than the amount of CO_2 emissions released into the environment. As shown in Figure 4B, the lifecycle total emission (including embodied emission and operational emission) can be reduced from point 1 to point 2 through the original material preparation, intelligent robot construction, energy-saving designs, etc. By adopting carbon offsetting (such as renewable power supply for the replacement of fossil fuels) or carbon elimination approaches (such as carbon capture and storage, photosynthesis for conversion from CO_2 to an organic compound), the system energy paradigm

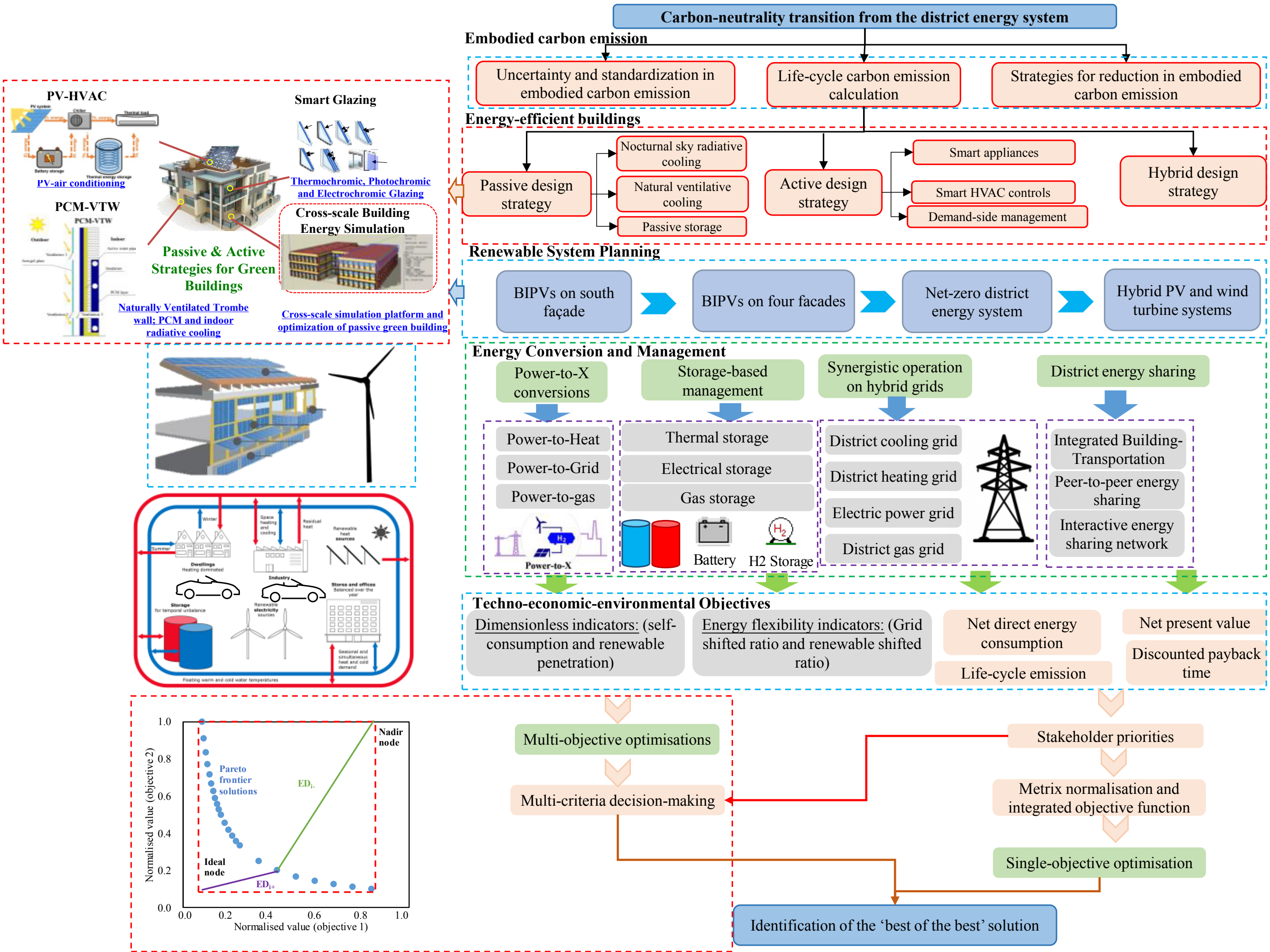

Figure 3. An overall framework of the research methodology for carbon-neutrality transition of energy districts.

can be transited from point 2 toward point 3, achieving a lifecycle carbon-neutral district.

In terms of the energy transition paradigm, strategies during the operational period mainly include energy-efficient buildings, renewable systems for cleaner power production, advanced energy management strategies with clean energy storage, and so on. Renewable energy sources, such as free-cooling ventilation, solar energy, and large-scale geothermal energy, and advanced demand-side management strategies are effective solutions for the energy transition towards a low-carbon economy. Furthermore, the embodied emissions can be reduced via novel offsite paneled modular frames, original material preparation, intelligent robot construction, optimum sustainable design model, and pre-defined strategies. Lizana et al.[39] systematically reviewed low-carbon buildings with thermal energy storage. Dirutigliano et al.[40] provided ranking priority on complex design energy retrofit options for the transition towards energy-efficient cities, in terms of energy consumption and GHG emission. A series of retrofit alternatives can be provided to district designers, energy planners, and decision makers.

Case study and international projects. Several projects have been initiated to promote the carbon-neutrality transition. For urban transition and sustainable urbanization, the Programme on Positive Energy Districts and Neighbourhoods was established in 2018 aiming at deploying and replicating 100 'Positive Energy Districts' across Europe by 2025.[41] Positive Energy Districts (PEDs)[42] aim to provide more supply of energy than the energy consumption in the city-scale boundary with minimum impact on energy networks through storage and energy flexibility. IEA EBC Annex 83 project proposes several subtasks for PEDs, including an in-depth definition of multi-stakeholders, technical solutions for PED transition from building, district and city-scale levels, development of digitalisation technologies (smart metering, big data, data management, smart control), and economic-social-environmental impacts for the planning and implementation of PED.

In terms of positive district energy transition in Europe, Groningen (Netherlands) and Oulu (Finland) act as pioneers, followed by León (Spain), Bassano del Grappa (Italy), Kadiköy (Turkey), Poprad (Slovakia), Vidin (Bulgaria) and Lublin (Poland), providing effective energy planning and control strategies. The MAKING-CITY project, financially supported by the EU HORIZON 2020 program, focuses on urban energy planning for the energy transition. Shnapp et al.[43] combined scientific research and realised projects for the zero-energy district (ZED) or positive energy district with cost-benefit calculation methodology and co-benefits to the citizens and local authorities. Success factors in energy efficiency and PED project implementation are shown in Figure S1.[44] Projects collected by JPI Urban Europe in a PED Booklet, provide an accumulated experience for achieving 100 PEDs until 2025. The 61 studied cases have been classified into PED and towards PED with critical factors, as demonstrated in Figure S1, where stakeholder involvement prioritizes other factors, followed by integrated technologies and business models. Therefore, advanced education of stakeholders and the development of integrated technologies play significant roles in the PEDs transition.

Embodied carbon emission in building energy districts

Uncertainty and standardization in embodied carbon emission. In terms

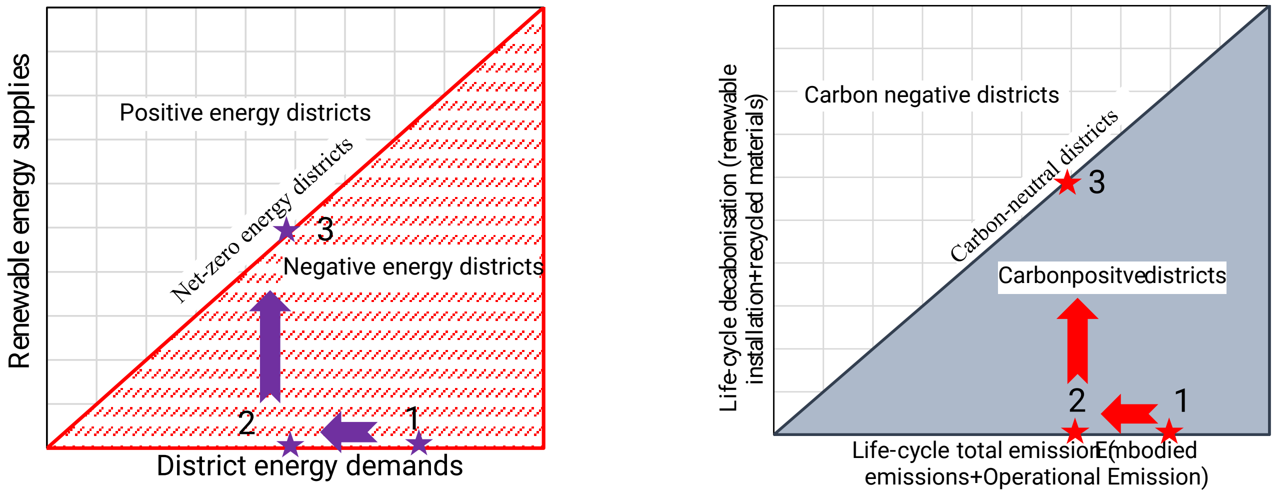

Figure 4. Demonstration of (A) negative, net-zero and positive energy districts; (B) lifecycle carbon-negative, carbon-neutral and carbon-positive districts.

of the input parameters' uncertainty, uncertainties of LCA emissions can be classified into parameter, scenario, and model uncertainty. Zhang et al.[45] comparatively studied deterministic and stochastic approaches for carbon emission of the building sector. Results showed that the input parameters uncertainty will lead to a standard deviation of 3106 tCO_{2e} with a sample mean of 61504 $tCO_{2,}$ i.e., around 5%. Chastas et al.[11] normalized carbon emissions in buildings for further standardization in LCA. Results showed that the embodied carbon emissions accounted for 9%-22% of the LCA emissions of conventional buildings, 32%-38% for passive buildings, and 21%-57% for low-energy buildings.

Compared to operational carbon emissions, the embodied carbon emissions are more complicated, due to the uncertainties from certain methodological and data quality parameters. Embodied energy can be classified into initial embodied energy (IEE) in building construction, and recurrent embodied energy (REE) for energy embodied in maintenance, repair, and replacement processes. Modeling techniques and analysis approaches have been explored by several researchers. Dixit[12] systematically reviewed the calculation approach for life cycle recurrent embodied energy. Standardized database and calculation method for REE with probabilistic models based on past data, can promote the uncertainty quantification, with respect to various geographic locations with different environmental qualities. Dixit[13] comprehensively reviewed modelling techniques for initial and life cycle embodied energy quantification and highlighted the necessity for parameters' standardization with uncertainty calculation models. Robati et al.[14] adopted the random sampling approach to quantify the uncertainty of embodied carbon emission by conducting Monte Carlo simulations. The uncertainty analysis indicates that the total embodied CO_2 emission is between 2951 to 5254 t.

Software and tools for lifecycle carbon emission calculation. In respect to the difference in Life Cycle Assessment results, Silva et al.[46] conducted a comprehensive cause–effect analysis, and concluded that the discrepancy was mainly due to the import process from different background datasets (e.g., Chinese Life Cycle, Ecoinvent, and European Life Cycle Databases), and the lack of standard Life Cycle Impact Assessment implementation methods. In order to quantitatively evaluate the lifecycle carbon emissions, advanced techniques with a combination of different software tools have been employed. Software and tools for LCA carbon emission are shown in Figure B, which demonstrates the recent advances in software and tools. Rossi et al.[47] developed a basic tool for lifecycle assessment, the Pleiades + Comfie software combined with Equer, which is effective for the quantification of embodied energy, embodied carbon, and operational carbon. Kang et al.[48] adopted a probabilistic method to calculate and quantify the uncertainty of embodied carbon emissions from building constructions. Compared to the deterministic values, the probabilistic-based uncertainty analysis is necessary for embodied carbon emissions. Data sources for embodied emissions can be obtained from the construction process and Environmental Product Declarations (EPDs) by manufacturers[49] in the 'cradle to factory gate' phase, database in commercial and in-house software tools during 'cradle to grave' phase. Kalakul et al.[50] developed a new LCA software, LCSoft, which can integrate LCA in sustainable design (SustainPro), economic analysis (ECON), and process simulation. There are four tools for different application purposes, i.e., Tool-1 for life cycle inventory (LCI) knowledge management, Tool-2 for estimation of environmental impact, Tool-3 for LCA calculations on a model library, and Tool-4 for interface integration with other tools.

Greenhouse gas (GHG) emissions, mass ratio and material ratio in the life cycle stage for a residential building are demonstrated in Figure S3. As shown in Figure S3A the GHG emissions of a residential building during the operation phase shows the largest proportion at 69%, followed by the building material production at 24%. With respect to the mass ratio of building materials, as shown in Figure S3B, the concrete accounts for the largest share at 82%, whereas the steel and aluminum show a relatively low ratio at 4%. In respect to the ratio of material-related GHG emission, as shown in Figure S3C, the shares of concrete, steel and aluminum are 44%, 28%, and 17%, respectively.

Strategies for the reduction in embodied carbon emission. Scientific literature demonstrates different ways to reduce embodied carbon emissions, e.g. through renewable power supply,[52] novel offsite modular timber frames,[53] optimum sustainable design model,[15] and pre-defined strategies [16] in respect to building materials (concrete, steel and timber), and transportation activities.[54] Kayaçetin and Tanyer[55] quantified the constitution of embodied carbon and indicated that the average of total embodied carbon emissions is 409.2 kg $CO_{2\text{-}eq}/m^2$, with buildings at 272.4 kg $CO_{2\text{-}eq}/m^2$ (66.6%), structural landscape at 37.4 $kgCO_{2\text{-}eq}/m^2$ (9.1%), and transportation infrastructure at 99.4 $kgCO_{2\text{-}eq}/m^2$ (24.3%). Lobaccaro et al.[52] studied the impact of the parametric design approach (building shape, the dimensions of construction components, and the quantity of materials) on embodied GHG emissions. The results showed that embodied and operational emissions can be counterbalanced through renewable power supply. Monahan and Powell [53] applied a modern method of construction (MMC), using a novel offsite panelized modular timber frame system to reduce the embodied carbon. Compared to traditional methods, the MMC can reduce the embodied carbon by 34%.

In addition, researchers have also focused on effective strategies for reducing embodied energy and emissions. Gan et al.[54] comparatively studied embodied carbon in reinforced concrete buildings with different material designs and provided decision support tools for low embodied carbon in buildings. Instead of using the databases-based industry-average value for the LCA, Shadram et al.[56] developed an integrated BIM-based framework with Extract Transform Load, considering individual material in the supply chain. Results showed that an obvious decrease in building energy use and carbon footprint can be realized during the design process. Oh et al.[15] developed an optimum sustainable design model for CO_2 emission reductions. The application of the proposed method in an office building can lead to a decrease in embodied carbon emissions by 15.8%. Teng and Pan[16] adopted pre-defined strategies to reduce embodied carbon of prefabricated high-rise buildings in Hong Kong. The results showed that the average embodied carbon is 561 kg CO_2/m^2, and key factors on embodied carbon include the production of concrete, steel and timber, and transportation activities. Recently, multidisciplinary studies have been undertaken using artificial intelligence for the reduction of embodied carbon emissions. In order to identify high-strength concrete mixes and minimize the embodied carbon, Thilakarathna et al.[17] developed data-driven models trained by machine learning algorithms. The machine learning model is an effective tool to reach the trade-off solution between embodied carbon emission and compressive strength.

RESULTS

Passive and active strategies from the district demands

From the perspective of district energy demand, passive designs for energy-efficient buildings have widely been deployed, mainly including natural ventilation, nocturnal sky radiative cooling, and passive thermal storage. This section aims to comprehensively review the passive strategies for energy-efficient buildings, in terms of system types, operational controls, energy-saving mechanisms and results.

Passive strategies for energy-efficient buildings

Natural ventilation for cooling and heating. Natural ventilation, with the driving force of buoyancy, has been regarded as one of the typical energy-saving strategies and has been widely applied in cooling and heating scenarios. Table S1 summarises the ventilation for heating and cooling. In terms of the natural ventilation for heating, Kim et al.[62] studied the natural ventilation in a double skin envelope (DSE) to reduce the heating load in winter. Results showed that the thermal buffer can lead to a decrease of the heating energy consumption by 14.7% in January. Heracleous and Michael[69] investigated the impact of natural ventilation on the improvement of thermal comfort and indoor air quality during the heating season. In terms of the natural ventilation for cooling, researchers have been focused on modelling development,[64] reduction in primary energy consumption,[58] smart controls,[65] and potential assessment.[66] Ahmed et al.[67] studied natural ventilation in warm climates. O'Donovan et al.[64] developed a numerical model to predict the naturally ventilated air temperature. The model can be used for the identification of the most influential factors on physical parameters, and diversity quantification in opening control strategies and occupant behavior. In respect to a near zero-energy educational building, Gil-Baez et al.[58] indicated that, compared to mechanical ventilation, natural ventilation can reduce the primary energy consumption between 18% and 33%. Nomura and Hiyama[59] provided a review on natural ventilation in office buildings in Japan. Results showed that building shape and air change rate are critical elements that need to be considered during the design stage. Sakiyama et al.[66] assessed the natural ventilation potentials, in accordance with weather analyses and building simulation. Furthermore, the neighborhood-scale microclimate will affect the night ventilation cooling potential. Xie et al.[68] indicated that the courtyard form could reduce heating demand and enhance night ventilation cooling. Meanwhile, the meteorological data from different years will lead to 26-31% underestimation (typical meteorological year, TMY) and 9-14% overestimation (actual meteorological year, AMY) of the night ventilation cooling potential. A ventilated Trombe wall system for space heating as shown in Figure S4.[63] Elghamry and Hassan[63] experimentally studied a ventilated Trombe wall system for space heating, as shown in Figure S4. Results showed that the room temperature can be maximally increased by 14 °C for the ventilation integrated heating system.

Diurnal and nocturnal sky radiative cooling. Sky radiative cooling, with the cooling source from the outer space, is emerging and becomes attractive, due to the abundance in cooling potentials, simplification and compactness in system design. Depending on the time duration for cooling energy exploitation, the sky radiative cooling can be classified into nocturnal and diurnal sky radiative cooling. Compared to the nocturnal sky radiative cooling, the diurnal sky radiative cooling has several challenges, resulting from the intensified solar radiation. Table S2 shows the overview on diurnal and nocturnal sky radiative cooling, in terms of adopted approaches, advanced materials for reflection of solar radiation, integrated systems, and energy potentials.

Nocturnal sky radiative cooling[77] has widely been studied, in respect to cooling potential maps[70], advanced materials[73] for cooling capacity improvement, novel system designs[71–72,77] and etc. Zeyghami et al.[70] studied sky radiative cooling for building energy saving. Their review can provide radiative cooling potential maps for different climate regions. Eicker and Dalibard[71] experimentally studied the cooling power of night radiative cooling PV-thermal collectors. The results showed that the cooling and electric energies are 51 and 205 kWh/m^2·a, respectively. Vall and Castell[78] conducted a holistic review on radiative cooling for low-grade energy utilization. Recommendations for cooling efficiency improvement include a mental cover, replacement of air by water as heat-carrier fluid, heat storage integration, advanced materials with improved radiative properties and modelling for accurate prediction on infrared atmospheric radiation. Yan et al.[72] proposed a heat removal strategy by nocturnal sky radiation to dissipate the accumulated heat in PCM walls. The results showed that 54.7%-81.0% of the resisted heat by PCM wall can be dissipated by a nocturnal radiation cooler at night. Raman et al.[77] adopted a photonic solar reflector and thermal emitter with seven layers of HfO_2 and SiO_2, to realise passive radiative cooling. This novel component can reflect 97% of incident sunlight and selectively emit thermal energy in the atmospheric transparency window. Katramiz et al.[73] integrated a radiative cooling panel with phase change material (PCM) storage to reduce the cooling load. The results showed that the combined diurnal and night radiative cooling (RC) panel can effectively decrease the PCM storage size by 12.3%.

Diurnal radiative cooling has also been studied with focus on advances in sub-ambient radiative cooling materials and system combination to reflect solar radiation and store the radiative cooling energy. Lu et al.[79] comprehensively reviewed passive radiative cooling techniques in buildings. The results showed that daytime radiative cooling energy density is rather low. The cooling potentials are mainly limited by coating material constraints and technique reliability. Yin et al.[80] reviewed sub-ambient radiative cooling materials for passive radiative cooling during the daytime, e.g. by employing the universe as a cold source for energy-efficient cooling. Li et al.[76] reviewed the fundamentals, materials, and applications of daytime radiative cooling. The results showed that advanced materials and novel structure designs are critical for the enhancement in daytime radiative cooling. Tso et al.[75] conducted field tests on passive radiative cooling generators with different designs, i.e., non-vacuum, and vacuum with seven potassium chloride (KCl) windows and a single KCl IR-pass window. The results showed that the ambient air temperature can be reduced by about 6-7 °C in the passive radiative cooler with seven KCl windows and a cooler without vacuum. However, under the meteorological conditions in Hong Kong, there is no cooling effect during the daytime. Furthermore, the combined systems have been studied to enhance the cooling capacity. Katramiz et al.[74] combined the diurnal and indirect evaporative cooling system in an arid climate. Compared to the only dew point indirect evaporative cooling systema, the integration of a radiative cooling panel can reduce the water consumption by 44.2%. The combined cooling solutions will reduce the electrical energy consumption by 53.4%.

Passive thermal storage. Energy storages on passive strategies have been studied, in terms of sensible and latent energy forms, as listed in Table S3. Depending on the magnitude of energy storage density, passive storage techniques can be mainly classified into thermal mass storage and latent thermal storage. Compared to the thermal mass storage with sensible specific heat capacity of concrete, the latent thermal storage with phase change materials shows a higher energy storage density, whereas the associated initial investment and maintenance costs are increased. In respect to thermal mass storage, Rodríguez et al.[81] designed PV and building thermal mass storage for improving indoor thermal comfort. Sameti and Haghighat[82] studied the optimal design and operation of distributed energy storage for net-zero energy districts. Pareto optimal solutions driven by multi-objective optimizations can minimize the total annualized cost and equivalent CO_2 emissions with reliable system operation. Reilly and Kinnane[83] conducted annual performance simulations to investigate the effectiveness of thermal mass storage in cooling conditions. Their results showed that the stored cooling energy is much higher than the stored heating energy, leading to an increase in energy consumption. In addition to thermal mass in the building envelope, the sensible storage in furniture will shave the peak cooling load by a median value of -2.3%.

Compared to thermal mass storage, latent thermal storages have attracted more interest, mainly due to the considerably higher energy storage density, stability in chemical property, nearly constant fusion temperature. Lizana et al.[90] comprehensively reviewed the development of PCMs in passive thermal storage. The volumetric thermal energy storage density is between 430 and 250 MJ/m^3. Johra and Heiselberg[88] provided a holistic overview of PCM integration in furniture for building energy storage. Advantages include the large surface area and no additional construction costs. Furthermore, the combined PCM and natural ventilation have also been studied, for the enhancement in natural energy utilization. Piselli et al.[89] analysed the energy performance of a PCM integrated building façade with natural ventilation. The results showed that around 300 kWh/year cooling energy can be saved in mild climates.

Active strategies for energy-efficient buildings

Smart appliances. Energy intelligent buildings with advanced energy management and smart controls are emerging as energy-efficient buildings with low-carbon emissions. An intelligent building is shown in Figure S5 with wireless power supply systems and internet of thing (IoT)-based smart meter for energy management. An intelligent building is shown in Figure S5, with wireless power supply systems and internet of thing (IoT)-based smart meter for energy management. Zhang[89] designed a fractional-order time-sharing-control-based wireless power supply system, to reduce the complexity and cost of wired power supply systems. Instead of controlling series-parallel capacitors through a series of relay switches, only one fractional-order capacitor is required to realize the time-sharing resonant charging. Sovacool et al.[92] reviewed the benefits and risks of smart home technologies, involving control, and socio-technical systems, practices, and justice. As shown in Figure S5, Karthick et al.[93] designed an IoT-based smart meter for energy management. The IoT-based smart energy management is an effective approach for distributed energy dispatch with power supply reliability and demand flexibility.

Smart HVAC controls. As over 60% energy consumption of buildings was attributed to HVAC systems, researchers mainly focused on smart HVAC controls for energy-efficient buildings. Table S4 lists the holistic overview of smart HVAC controls, with respect to smart and intelligent ventilations, metering, hydronics with pumping systems, radiant cooling and heating systems. In terms of smart and intelligent ventilations, Chen et al.[65] developed a model predictive control on mixed ventilation, and their proposed strategy shows the highest energy saving potential and occupant satisfaction. The results showed that the automatic natural ventilation control has the highest energy saving potential and occupant satisfaction. Zhou et al.[95] developed a machine learning-based smart control on a PCMs-Trombe wall. The predicted performance via the surrogate model can effectively improve the energy storage efficiency of natural cooling sources. Heo et al.[96] developed a deep reinforcement learning-based autonomous ventilation control. By applying the control in a subway station, the energy consumption can be reduced by up to 14.4%. Rey-Hernández et al.[97] analyzed the impact of hybrid ventilation strategy on net-zero energy buildings. By following the principle to keep the Indoor Air Quality (IAQ) within the allowable limits, to maximize the use of natural resources and to minimize the energy consumption and carbon emissions, results showed that the hybrid ventilation system can operate with 70% of the operational time, leading to significant energy saving of the HVAC systems. Considering the lack of data for model training to capture the dynamics of complicated building physics, Chen et al.[98] adopted transfer learning with deep neural networks to reduce the required on-site training data with the data from an already pre-trained multi-year database. The results showed that compared to the model trained by source data or target data, the proposed transfer learning model shows higher accuracy in predictions of indoor air temperature and relative humidity. Southall et al.[99] preliminarily studied the impact of ventilation demand control on space heating consumption and indoor air quality. The results showed that, under a climate representative of the Atlantic Central climate zone, compared to the uncontrolled system, the proposed strategy can decrease the energy consumption of around 15 kWh/m^2·a by 58%.

From aspects of smart metering in residential heat pump systems, Fischer and Madani[100] comprehensively reviewed practical control approaches and smart grid-response operation to provide system energy flexibility, from buildings to the power grid. Furthermore, radiative cooling/heating with embedded active sources is energy-saving. Hanif et al.[101] developed a radiator with a flat-plate rooftop and indicated that the power consumption for cooling could be reduced by 11% for radiative cooling.

Demand-side management. Demand-side management, as shown in Figure S5, plays a critical role in low-energy buildings with energy flexibility. Ren et al.[115] comparatively studied four different DSM strategies, as shown in Figure S6, i.e., over-heating/cooling, pre-heating/cooling, temperature set-point relaxation, and heat pump charging thermal storage tank, for system energy flexibility improvement. Results showed that, the DSM strategies can improve the solar contribution to 0.79, and the thermal energy storage unit can improve the solar contribution to 1.0. Core techniques include non-linear building demand prediction[108] with a high accuracy and efficiency, indoor occupancy prediction,[109] dynamic state prediction of thermal and electrical systems. In terms of building demand predictions, Ahmad and Chen[108] comparatively studied three variant machine-learning models in energy demands prediction, and the results can provide advanced modelling tools for accurate performance prediction. Zhou and Zheng[20] developed a surrogate model with supervised learning to predict the energy demand of an office building with scenario uncertainty. The model can help in developing hybrid demand-side controllers.

In respect to the indoor occupancy prediction, Ryu and Moon[109] developed a data-driven model for occupancy prediction using indoor environmental data. The model with indirect approach can address the privacy concerns and inaccurate measurements of direct approach. Huchuk et al.[110] developed a machine learning model to predict the indoor occupancy via thermostat data. Results showed that the random forest algorithm shows the highest prediction accuracy. By incorporating the dynamic performance prediction, advanced demand-side management (DSM) has been developed on thermal and power systems for an energy flexible community, as listed in Table S5.

By incorporating dynamic performance prediction, advanced demand-side management (DSM) has been developed on thermal and power systems for an energy flexible community as listed in Table S5. In respect to heating/cooling systems, Brusco et al.[111] applied demand response to develop the energy management strategy, so as to maximize the coalition utility and reduce the reverse energy flows, through a coalition coordinator. By adopting the machine learning algorithms for model performance prediction, Pallonetto et al.[112] developed a prediction-based approach to dynamically control the integrated heat pump and thermal storage systems, based on time-of-use electricity tariffs and indoor thermal environment. Results showed that, compared to the baseline reference case, the predictive algorithm can reduce the electricity end-use cost by 41.8%, the utility generation cost by 39%, and the carbon emission by 37.9%. In respect to occupants' stochastic behavior, Peng et al.[113] developed a machine learning (ML) based demand-driven control strategy to smartly control the indoor air setpoint temperature. The experimental testing results showed that compared to the pre-scheduled cooling operations, the ML based demand-driven control can realise 7-5% energy savings. Li et al.[114] studied the demand-side management strategies of a daily thermal consumption and production of cogeneration systems (such as heat pumps and fuel cells) to improve the local electricity self-sufficiency ratio and reduce net load fluctuations. The results showed that the PV systems can mainly reduce the system cost, and fuel cells lead to decrease in CO_2 emissions. Ren et al.[115] comparatively studied four different DSM strategies as shown in Figure S6, i.e., over-heating/cooling, pre-heating/cooling, temperature set-point relaxation, and heat pump charging thermal storage tank, for system energy flexibility improvement. Results showed that, the DSM strategies can improve the solar contribution to 0.79, and the thermal energy storage unit can improve the solar contribution to 1.0. Stavrakas and Flamos[116] developed a modular demand-side management model for demand flexibility enhancement of a residential building. Vivian et al.[117] developed a heat pump scheduling shifting strategy to flatten the power profile with peak shaving. Results showed that, the daily peak power can be reduced by 21% and 35%, when only considering space heating, both space heating and domestic hot water, respectively. In respect to power energy systems, Groppi et al.[118] reviewed the DSM strategies for power-to-transport solutions (hydrogen-fueled and electric-powered vehicles and ferries) to avoid the excess power production and improve the grid stability. Xu et al. [120] studied smart electric vehicles (EVs) charging/discharging strategies, to reduce the power cost of microgrid. The price-based DSM for residential prosumers can reduce the seasonal peak consumption by around 3.2%, and the overall consumption by approximately 2%.

Hybrid strategies for energy-efficient buildings. With complementary passive and active strategies, hybrid strategies have been studied on thermal and electrical energy systems. In respect to thermal systems, hybrid strategies include hybrid natural and mechanical ventilation,[123–124] sensible and latent thermal storages,[125–126] active and passive radiative cooling/heating[127-129]. A novel PCM-ventilated mortar block for floor heating/cooling was designed as shown in Figure S7. Guo et al.[124] designed a novel PCM-ventilated mortar block for floor heating/cooling as shown in Figure S7. The experimental testing results showed that, the demand cooling time can be reduced by 22.7%-25.6% with the implementation of ventilation. Hybrid strategies for energy-efficient buildings are summarized in Table S6. Zhou et al.[127] reviewed the passive and active strategies PCM thermal storage for energy efficient buildings. Compared to passive strategies, the active strategies are more flexible in load reduction or shifting and stabilization in indoor air temperature. In respect to electrical systems, Chinde et al.[130] indicated that ancillary services and voltage management can effectively improve electric grid reliability. By activating the energy flexibility, the district coal dominated power system in the Beijing-Tianjin-Hebei Region can incorporate 125.9 GW of wind power and 44.3 GW of PV systems by 2035 contributing to the realization of the Chinese carbon-peak goal.

Energy planning on 'source-grid-load-storage' framework

Building integrated solar PV systems—passive and active PV cooling strategies. In California, U.S.A., rooftop PV can provide sufficient power to cover the energy demands,[133] whereas full installation of BIPVs on four facades can provide only around 20% of the energy demand in Hong Kong.[19] The popularity of BIPV is mainly due to the spatial saving and abundant solar resources making it suitable in highly dense metropolitans, such as Hong Kong, Singapore, etc. Photovoltaic windows can reduce 40% of carbon emissions in buildings.[134] However, the main challenge is the high solar cell temperature, leading to lower solar-to-power conversion efficiency. The state-of-the-art PV cooling techniques can be mainly classified into ventilative PV cooling, sky radiative cooling, phase change material-photovoltaic (PCM-PV) cooling, water-based PV cooling and slits on the PV panel surface. PV cooling strategies are summarized on Table S7. Ventilative cooling techniques include naturally ventilated BIPV modules[139] and wind-driven convection for PV cooling.[135] In respect to the sky radiative cooling of PVs, Wang et al.[136] indicated that the solar cell temperature can be reduced by 36 °C increasing the open-circuit voltage by 31%. Passive PCM-PV cooling technology has also been studied due to the high energy density, nearly constant phase change temperature and stability in thermochemical property of PCMs. A systematic review on PCM-based PV cooling techniques has been conducted.[128] The review highlighted the importance of advanced machine learning techniques for optimal design. In addition, water-based PV cooling [137–138] has also been studied with enhancement in heat transfer and heat dissipation.

Floating PV farms, onshore/off-shore wind turbines and optimal layout

Floating PV farms. Considering the critical challenges of BIPV, such as overheating of the solar cell, low solar-to-power conversion efficiency, and performance degradation, floating PV systems have recently emerged with advantages of high-power efficiency due to the low surrounding temperature, avoidance of algae, reduction in water evaporation, spatial space saving, etc. Researchers mainly focused on performance degradation,[145] payback period,[146–147] trade-off strategy for multi-criteria performance,[148] and paradigm transition for district energy systems.[149]

Goswami and Sadhu[145] studied the annual performance degradation of a floating solar photovoltaic (FSPV) system. Compared to the land-based PV system with the degradation rate at 1.07%, the FSPV shows the degradation rate at 1.18% for 17 months. Clemons et al.[146] conducted a life cycle assessment of a floating photovoltaic (FPV) system. Compared to the polycrystalline and thin film with the payback period at 7.8 and 16.3 years, the payback period for FPV was 7.5 years. McKuin et al.[147] studied the techno-economic effects of over-canal solar cells in California's 6,350 km long canal network. The results showed that compared to land-based PVs, the over-canal solar PV showed a higher net present value of 20–50%. A floating photovoltaic system is illustrated in Figure S8, with trade-off strategies on power generation, water evaporation and algal growth. Zhang et al.[150] comprehensively studied the multi-criteria performance of a floating photovoltaic system with trade-off strategies, in terms of power generation, water evaporation and algal growth, as illustrated in Figure S8. The results showed that an optimum trade-off between power generation and transparency can be reached with a maximum efficiency of 13% and average visible transmittance over 20%. Dai et al.[150] conducted structural and hydro-elastic performance analysis on a floating modular photovoltaic system. Results can promote applicability of the innovative floating systems in renewable power supply. Using FPVs Zhou et al.[149] studied the energy transition paradigm from negative to positive energy districts. The results showed that the average annual net direct energy consumption can be decreased from 249.1 to −343.3 kWh/m^2·a.

The impact of FPVs on ecological systems has also been studied. Haas et al.[151] comprehensively studied the ecological impacts of FPV fraction on power generation, microalgal growth and hydropower revenue. The results showed that when the FPV fraction is between 40–60%, the good trade-off between algal blooms and economic hydropower losses can be reached.

Optimal layout of wind turbines. In addition to solar energy, wind resources have also been utilized for clean power production. Research is mainly focused on turbine wake model development, parametric analysis, layout optimization and uncertainty-based multi-objective optimisation, as listed in Table S8. Brogna et al.[152] developed a new wake model, to improve the performance prediction accuracy, and guide the wind farm layouts. Sahebzadeh et al.[153] conducted a parametric analysis on distance and angle to effectively improve the power generation. The optimal layout of wind farm has been studied with genetic algorithm,[154] mixed-discrete Particle Swarm Optimization (MDPSO) algorithm,[155] to improve the aggregated power generation. Furthermore, considering the uncertainty in wind speeds and directions, Mittal et al.[156] conducted uncertainty-based multi-objective optimizations. The results showed that the optimal turbine layout can improve the power generation by 49%.

Thermal, electrical and hydrogen energy storage. Thermal, electrical and hydrogen energy storages are useful to reach carbon-neutrality as summarized in Table S9. Sensible and latent thermal storage for renewable energy utilization (such as solar energy,[159-161] wind energy, geothermal energy[162–163] and etc.) are full of intriguing prospects for low-carbon energy systems. Hacker et al.[164] indicated that although the heavy envelope shows a higher initial embodied CO_2 by 15% (4.93 t), the savings in operational CO_2 emissions will offset the increase. Overall, the total savings of up to 17% (35.7 t) in lifecycle CO_2 can be realised in the heaviest building envelope. By integrating PCMs in building envelopes, Kočí et al.[165] indicated that, depending on the meteorological parameters, heating and cooling loads can be reduced with between 3.7 and 6.5 kWh/m^2. Electrical energy storage plays significant role in the carbon-neutrality transition. Sharifzadeh et al.[166] studied pumped hydroelectric energy storage for low-carbon electricity with integration of carbon capture and renewable energy technologies. The electrochemical battery storages can reduce the global GHG of EVs,[167–168] whereas the consideration of battery degradation will increase the GHG emission by 30%.[169]

Combined heat and power with thermal storage can effectively decarbonize energy systems in buildings and industries.[171] As an intriguing energy carrier with high energy density and by-product of water, hydrogen energy plays critical roles in carbon-neutrality transition. Figure S9 shows the diagram between carbon emission factor (CEF) and working temperature for hydrogen production.[170] As shown in Figure S9, the carbon footprints of the steam methane reforming (SMR), solar-based alkaline electrolysis, and thermochemical cycles are 10.6 kg/kg, 2–2.3 kg/kg and 4.3-4.5 kg/kg of H_2, respectively.[170] Petkov and Gabrielli[172] designed a seasonal energy storage with power-to-hydrogen conversion to realise a low-carbon multi-energy system. Results showed that the power-to-hydrogen conversion can effectively reduce the emission by 5-10%. Kakoulaki et al.[173] studied the decarbonization of hydrogen production at the regional level. They concluded that from the national district perspective, 88 regions (81%) show the renewable supply power higher than the demand, and 84 regions show over 50% excess renewable energy higher than the demand. Fózer et al.[174] designed a closed cycle for energy storage, CO_2 reuse and CH_4 production, involving microalgae CO_2 absorption, catalytic hydrothermal gasification and gas storage. The results showed a round-trip efficiency of 42.3% with an equivalent CO_2 emission factor of 99.4 g/kWh$_e$. Rehfeldt et al.[175] studied the potential of fuel switch towards biomass and electricity on GHG emissions and global warming. The results showed that with a fuel switch towards biomass and electricity, 34% (184 Mt) of the global emissions could be reduced in 2030. Klöckner and Letmathe[176] studied a series of strategies for decarbonization including renewable energy sources, energy-efficient heating systems, smart charging infrastructures and large-scale storages. Furthermore, the increase in rated capacity of domestic electrolyser can promote the phase-out of traditional fossil fuels.

Energy conversion and management strategies towards the carbon-neutrality

From the perspective of system operation, multiple and combined strategies can be applied for the energy transition towards carbon-neutrality with advanced energy conversion and management strategies shown in Figure S10. As shown in Figure S10 considering dynamic grid information (e.g., time-of-use grid electricity, peak power, ramp rate and so on) grid-responsive controls can be applied in respect to smart appliances, flexible power-to-X energy conversions, and energy storage management. Furthermore, the synergistic operation of multi-energy networks[187] (e.g., cooling, heating and power grids, carbon and hydrogen networks) can improve the power supply reliability, system decarbonization, and carbon-neutrality transition. Table S10 shows an overview on energy conversion and management strategies for low-carbon transition from perspectives of power-to-X conversions, diversified energy storage forms, synergistic grids' interaction and district energy sharing.

Power-to-X conversions. Power-to-X conversions have been widely adopted for renewable penetration enhancement, power supply reliability in respect to intermittent renewable generation, cascade energy utilization, and so on. Zhou and Cao[18] designed renewable-to-heat conversion strategies to charge the cooling storage tanks with a high coefficient of performance (COP) as demonstrated in Figure S11. Zhou and Cao[18] designed renewable-to-heat conversion strategies to charge the cooling storage tanks with a high coefficient of performance (COP). As demonstrated in Figure S11, the surplus renewable energy is used to activate the excess renewable-recharging chillers, instead of being exported to the grid or dumped to the environment. The proposed strategy can improve the renewable penetration ratio and load coverage ratio. Lim et al.[28] applied power-to-hydrogen and power-to-synthetic natural gas conversions, for GHG reduction and annual cost saving. The results showed that a 35% renewable energy penetration will reduce the annual greenhouse gas emission by $1.24X10^6$ tons. By utilizing the low-price grid electricity, the carbon dioxide from a geothermal plant can be conversed to synthetic methane, which can be a good alternative choice for the carbon-neutrality transition.

Storage-based energy management. Researchers focused on energy management strategies of thermal and electrical storages, for system decarbonization. Rule-based and model-predictive controls are most widely adopted strategies,[198] based on the real-time and short-term predicted signals[20] for reduction in primary energy consumption and GHG emission,[33] solar energy utilization[189] and cost saving.[32] In respect to thermal storages, Saloux and Candanedo[33] adopted a rule-based strategy on flow rate of the variable speed pump and temperature difference across solar collectors. The proposed control can reduce the electrical consumption of pump systems, energy costs and GHG emissions by over 40%, 34% and 29%, respectively. The proposed model-predictive control on HVAC systems can reduce the cooling electricity consumption by 36.7% in the lecture theatre. In terms of electric storages, Zhou et al.[21] proposed a heuristic battery-protective strategy to decelerate the battery cycling ageing rate. The improvement in battery relative capacity from 0.921 to 0.981 will improve the system capability for high renewable penetration. Khemakhem et al.[199] developed a collaborative energy management strategy to flatten the power demand curve, through the smart EV charging. Through the local control (the availability of plug-in EVs,[200] the arrival and departure times and the initial state of charge) and the global control (the total power demand and the availability of EVs' neighbors), a flattened demand curve can be generated with the peak shaving and valley filling.

Hybrid grids' interaction for decarbonization and carbon-neutral transition. Considering the difference in intrinsic characteristics of different energy forms in terms of power response, energy density, charging/discharging constraints, synergistic operations and flexibility between different energy grids have been investigated. Tol and Svendsen[201] studied the dimension of piping networks and network layouts for low-energy district heating (DH) systems. The proposed dimensioning method can be applied for design of pipe diameters and DH network in low-energy districts. Lin et al.[194] studied the cooperation between hydrogen and smart power grids consisting of hydrogen energy, hydrogen fuel cell electric vehicles and hydrogen economy. Flexible integration strategy, dynamic monitoring on hydrogen energy and long-term storage are critical for the decarbonization transition. By smartly integrating heat pump to connect thermal and electrical micro-grids, Testi et al.[195] indicated that, the multi-objective stochastic optimization for robust control can realize 50% higher energy saving and 28% higher renewable production. The synergistic operation between hydrogen and electric grids indicated that a levelized cost of energy at 0.43-0.65 $/kWh can be achieved for the electrified and hydrogen based smart energy networks [196].

District energy sharing-generation and storage. Energy sharing networks are becoming more attractive for the improvement in renewable penetration and power supply reliability together with the decrease in grid reliance. Depending on the sharing items, district energy sharing can mainly be classified into renewable generation sharing and energy storage sharing. By integrating electric vehicle in office buildings for renewable energy storage Zhou and Cao[19] indicated that a 0.4 MW turbine and BIPVs can realize a zero-emission building-vehicle system. An energy sharing network was proposed by Zhou et al.[197] The multi-objective optimization on battery storage capacity and grid-to-battery charging power will reduce the equivalent CO_2 emissions from 147.4 to 136.4 kg/m^{2}a. Hakimi and Hasankhani[202] proposed an energy exchange method for energy sharing in district buildings. The energy interaction between smart homes is an effective solution for techno-economic performance improvement. Furthermore, energy storage sharing has also been studied. Carli et al.[203] coordinated the sharing between battery storage and renewable generation, based on an iterative finite horizon on-line optimization. The objective function included the self-supply with solar energy and the daily grid import cost under time-varying energy pricing. The results showed that the predictive control-based energy scheduling can improve the self-supply by 1.6% and reduce yearly energy cost by 8.2%.

DISCUSSION, OUTLOOK AND RECOMMENDATIONS

The carbon-neutrality transition requires a balance between the CO_2 production and reduction. Joint efforts with multidisciplinary research for the carbon-neutrality transition are demonstrated in Figure 5 showing an overview on the outlook and joint-efforts for the carbon-neutrality transition. Electrification and hydrogenation in multi-energy systems can replace traditional fossil fuel-based power contributing to the system sustainability. Technical, economic and environmental efforts are needed, including organic and recycled building materials, prefabricated and modular integrated construction techniques, net-zero energy buildings, zero-emission transportation, waste-to-energy and smart grid from technical perspectives. Economic efforts for the carbon-neutrality transition include cost decline in renewable and storage systems, economic rewards for efficient energy-use behaviors, economic incentives for renewable energy sharing and trading, and financial incentives in carbon trading market. The carbon-negative strategies include carbon capture and storage, photosynthesis for conversion from CO_2 to organic compound. Energy boundaries for lifecycle carbon neutrality include "cradle to gate","cradle to site", "cradle to end of construction" and "cradle to cradle". Factors for the carbon neutrality transition mainly include embodied emission in building materials and renewable systems, operational emission decarbonization from clean energy and materials recycling.

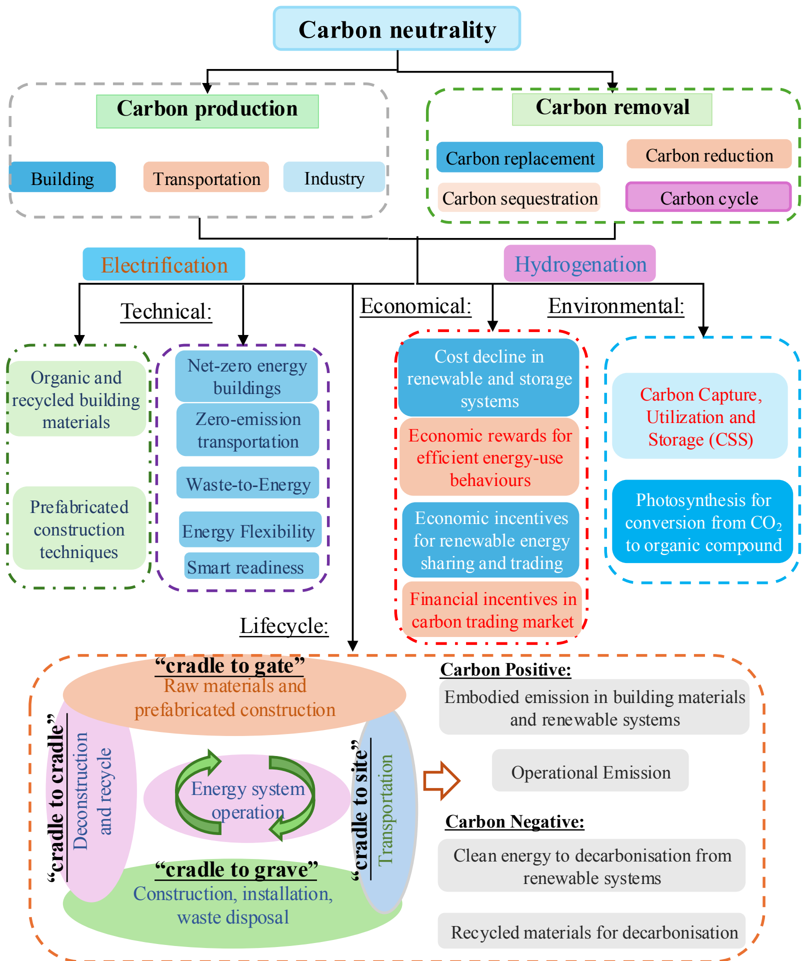

Figure 5. An overview on outlooks and multidisciplinary research for carbon-neutrality transition.

comprehensively reviewed the evolution of carbon footprint trends of metropolitans. The results showed that the average carbon footprint was decreased by 7% from 2006 to 2012. Furthermore, the increase in housing cost will lead to the decline of consumption-based emissions. The rapid decline of renewables and storage costs will promote the halve carbon emission.[205] Furthermore, city refurbishment plans are critical for positive energy districts.[206] Changes for positive energy districts transition include energy taxes for self-consumption, EU's general data protection regulation (GDPR) for data sharing and privacy, relevant laws and regulations to promote the participation of different fields.[207] Based on the lesssons learnt from France and Sweden for the net-zero energy transition, Millot et al.[208] indicated that public policies need to be developed, and continuous support needs to be given.

Carbon offsetting strategies include carbon capture and storage (CSS), photosynthesis for conversion from CO_2 to organic compound. However, the carbon capture and storage techniques are not mature, and the associated devices are quite expensive. In the current stage, tree planting and afforestation are still powerful measures to contribute to the carbon-neutrality transition.

Electrification and hydrogenation for multi-energy systems

In order to realize the carbon-neutrality, electrification and hydrogenation for multi-energy systems are intriguing and promising options to replace traditional fossil-fuel powered systems. Main advantages include the clean power sources, high energy quality with high energy conversion efficiency, fast demand response, reliability in power supply, flexibility to surrounding grids, etc. Cleaner power productions for electrification mainly include solar, wind, geothermal, ocean energy resources, etc. The renewable-to-hydrogen conversion might attract interests in future energy systems due to the high energy density, clean by-product water and long-term storage stability, whereas the energy conversion efficiency needs to be improved mainly due to the associated heat cogenerated in the electrolyzer and fuel cell. Heat recovery techniques for system efficiency improvement include Organic Rankin Cycle, thermoelectric generator, thermally regenerative electrochemical cycles, preheating for H_2 discharge rate from metal hydride, preheating of H_2 and air for enhancement of fuel cell operating efficiency.

Technical, economic and environmental efforts

Furthermore, joint efforts are necessary from technical, economic and environmental perspectives. In terms of technical perspective, organic and recycled building materials, prefabricated construction techniques can produce environmental-friendly building material waste and reduce the labor cost. Meanwhile, during the operational phase, several critical elements can contribute to the smart energy systems, including net-zero energy buildings, smart EV charging/discharging, smart grid, energy flexibility and smart readiness.

From the economic perspective, there are several effective measures for the carbon-neutrality transition. The measures include cost reduction in renewable and storage systems, economic incentives for efficient energy-use behavior, economic incentives for renewable energy sharing and trading, financial incentives in carbon trading market, among others Ottelin et al.[204]

Energy-efficient buildings

Energy-efficient building with exploitation of renewable energy resources is one of most effective carbon elimination strategies. Based on the current status and research gaps in the academia, researchers need to focus on:

1) passive design with PCM for natural energy utilization, e.g., diurnal and nocturnal sky radiative cooling, smart ventilative cooling and heating, etc.;

2) passive and active PV cooling techniques for power efficiency improvement, with air-based or water-based cooling strategies;

3) artificial intelligence integrated advanced optimization approaches[159,209] to assist the optimal design and smart operation.

Smart management and controls

Based on the difference between energy supply, consumption, storage and back-up grid interaction, smart energy management and controls are critical and full of prospects for the carbon-neutrality transition, with the mechanisms of increase in renewable penetration, decrease in energy loss, and so on. Future studies need to focus on:

1) renewable energy penetration through power-to-X conversions, instead of dumping surplus power;

2) synergistic operations between thermal, electrical and hydrogen storage systems, so as to reduce the thermal storage loss, decelerate the degradation of electrical and hydrogen storages;

3) model predictive control for smart operation.

Energy boundary for carbon neutrality

Energy boundary for carbon neutrality includes cradle-gate, cradle-site, cradle-end of construction, cradle-grave and cradle-cradle stages,[210] as shown in Figure S11. The "cradle to gate" system boundary includes the preparation of raw materials extraction to the end of manufacturing and prefabrication.[211] The "cradle to site" includes the "cradle to gate" and the transportation process of product to construction site.[212] The "cradle to end of construction" includes "cradle to site", the construction and installation processes, together with the waste disposal process. The "cradle to grave" system boundary considers operations, maintenance and refurbishment.[213] With the involvement of deconstruction and recycling processes, the closed-loop life cycle named "cradle to cradle" can be achieved, which is meaningful for a comprehensive environmental assessment.[214] To realize the carbon-neutrality, the involved variables include embodied emission in building materials and renewable systems, operational emission decarbonization from clean energy and recycled materials. Future studies can be focused on:

1) business models and de-risking renewable energy investments[215] strategies need to be developed to accelerate the system decarbonization.

2) development of statistic database for embodied emission calculation, with respect to different types of building materials in different countries and regions;

3) novel offsite panelized modular timber frames, original material preparation, intelligent robot construction, optimum sustainable design model and pre-defined strategies.

Energy policies for decarbonization

As the pioneer energy scheme, energy policies play dominated roles for decarbonization, from perspectives of occupants' behaviors with energy-saving consciousness,[216] installation of renewable energy systems, energy management and smart controls for economic benefits, smart energy trading, promotion of electrification and hydrogenation in district energy systems and participation willingness from different stakeholders.

1) Dissemination and consciousness improvement on energy-saving behaviors to regulate occupants' behaviors in buildings;

2) Economic incentives on installation of distributed renewable systems in buildings, so as to improve the renewable sharing ratio and gradually reduce the traditional energy sources, like crude oil, fossil fuels etc.;

3) Grid feed-in tariff for renewable energy systems will motivate the householders to install distributed renewable systems on rooftops, buildings facades, surrounding area for geothermal energy utilization, and etc.;

4) Economic subsidy for the purchase of battery-based or fuel cell-based electric vehicles. Furthermore, the lower price of renewable-driven power or hydrogen than the power from traditional power plant or the hydrogen from chemical industry[217] will help to improve the penetration of renewable energy and decarbonize the energy system;

5) Identification on optimal peer-to-peer energy trading prices in the interactive energy sharing network with multilateral economic benefits,[218] will improve participation willingness of different stakeholders, such as owners of buildings and vehicles, intermediate traders and utility company of power grids.

Perspectives for 2060 carbon neutrality target in China

It is reported that the energy transition in urban residents has effectively reduced 2.2 million premature deaths in China from 1980 to 2014.[219] The impact of future energy transition on techno-economic-environment and social performances is of great significance.[220] In addition, from the lifecycle perspective, future efforts can be focused on:

1) development of low-carbon building materials (such as bio-based building materials) and structures, to reduce the carbon emission in raw material production stage;

2) carbon sequestration and sink capacity enhancement of buildings: porous materials (such as porous amine microcapsules, metal-organic framework,[221] and etc.) in permeable building envelopes or air exhaust systems for carbon capture in built environment;

3) energy electrification in buildings and enhanced power interaction between smart buildings and utility grid.

Figure 6 demonstrates the roadmap, initiatives and policy actions for 2060 carbon neutrality in China, including energy intensity and carbon intensity, pollutant emissions, energy structures,[230–231] decarbonization potentials for different scenarios.[222] The Five Year Plan (FYP) from 10^{th} to 14^{th} as shown in Figure 6A, aims at reducing the energy intensity and carbon intensity by around 65%. In respect to pollutant emissions in Figure 6B, the 10^{th} FYP reduced SO_2 and COD by 20% and 10%, respectively.[218] The follow-up 11^{th}, 12^{th} and 13^{th} FYP reduced pollutant emissions (SO_2 and COD) by 10%,[224] 8%[225] and 10%,[232] respectively. In order to achieve the carbon neutrality in 2060, renewable and sustainable energy transition in energy structures plays critical roles. As shown in Figure 6C, the proportion of coal consumption gradually decreases from 72% in 2005 to 62.5% in 2020. Meanwhile, the proportion of renewable energy supply increases from 5.7% in 2005 to 11.7% in 2015. In the 2060 carbon neutrality scenario, the ideal energy structure is assumed to be: 15% natural gas, 25% unclear energy, 20% biomass, 20% wind turbine, 15% solar PVs, and 5% others (like waste-to-energy). In addition, tree planting and afforestation, as one of effective carbon-negative strategies, can directly capture CO_2 through the photosynthesis process. As shown in Figure 6D, the past 10^{th}, 11^{th}, 12^{th} and 13^{th} FYP increases forest coverage to 18.2%,[223] 20%,[224] 21.66%[225] and 23.04%.[232] Decarbonization potentials for different scenarios from five models,[234-236] as shown in Figure 6E, indicates that, negative-emission strategies (like CCUS), renewable energy supply and energy-saving scenario require the decarbonization potentials at 3.85, 3.03 and 4.0 Gt CO_2 in 2060.

CONCLUSION

In this study, a cross-scale 'material-component-system' framework is formulated for climate change adaption, zero-carbon and Sustainable Development Goals (SDGs), and a lifecycle reinspecting approach is proposed with advanced carbon elimination and off-setting strategies in buildings. A nano/micro/meso/macro-scale framework with cross-disciplinary mechanisms is involved to promote zero-carbon buildings for 2060 carbon neutrality in China. Lifecycle processes include raw materials preparation and prefabricated components, transportation, building design and construction, building energy system operation and waste recycling. The reviewed carbon elimination strategies include renewable system planning, energy-efficient buildings with passive, active and hybrid strategies, advanced energy conversion and management strategies. Off-setting strategies mainly include carbon capture and storage, photosynthesis conversion through tree planting and afforestation. In order to replace the traditional fossil-fuel powered systems, energy forms transition from traditional fossil to electrification and hydrogenation for multi-energy systems are becoming the mainstream. Main advantages include clean power sources, high energy quality with high energy conversion efficiency, fast demand response, reliability in power supply, flexibility to surrounding grids, etc. Furthermore, considering uncertainty and multi-diversity for embodied carbon emissions, a state-of-the-art review was conducted on consistent database with standardization, software and tools for embodied carbon emission quantification, and strategies for lifecycle carbon reduction. The lifecycle reinspecting approach with a series of carbon-positive and carbon-negative strategies can pave path for the transition towards lifecycle carbon neutrality in buildings. Critical conclusions are summarized below:

1) The cross-scale 'material-component-system' framework for Sustainable Development Goals mainly involves nano/micro-scale advanced materials and meso/macro-scale source-grid-load-storage systems. Lifecycle carbon-positive towards lifecycle carbon-negative districts will additionally require carbon elimination approaches, such as carbon capture and storage, photosynthesis for conversion from CO_2 to organic compound, novel offsite panelized modular timber frames, intelligent robot construction, optimum sustainable design model and pre-defined strategies.

2) The embodied carbon emissions account for 9%-22% for conventional buildings, 32%-38% for passive buildings and 21%-57% for low-energy buildings. Due to uncertainties from certain methodological and data quality parameters, modeling techniques and analysis approaches on embodied carbon emission mainly include probabilistic models, the random sampling approach with Monte Carlo simulation, uncertainty calculation models for parameters' standardization, and so on. Standard databases for lifecycle carbon emission mainly include the Chinese Life Cycle Database, Ecoinvent database and European Life Cycle Database. The adopted software and tools mainly include building information modelling, Pleiades, Comfie, Equer, eBalance, LCSoft and so on, with multiple plug-in toolboxes. Strategies for reduction in embodied carbon emission include renewable power supply, novel offsite panelized modular timber frames, optimum sustainable design model and pre-defined strategies.

3) District buildings with high energy efficiency play significant roles in the overall chain for lifecycle carbon-neutrality transition, due to the largest share

Figure 6. Roadmap, initiatives and policy actions to achieve 2060 carbon neutrality in China:[223-229] (A) energy intensity and carbon intensity; (B) pollutant emissions; (C) energy structures;[230-231] (D) forest coverage ratio through tree planting and afforestation; (E) decarbonization potentials for different scenarios.[222] (Note: increase forest stock volume to 16.5 billion cubic metres in 2020 230; increase forest stock volume by 4.5 billion cubic meters from 2005 levels in 2030 231. FYP and INDC refer to Five-Year Plan and Intended Nationally Determined Contributions.)

of carbon emission in buildings. Passive designs for energy-efficient buildings have been widely deployed, mainly including natural ventilation, nocturnal sky radiative cooling and passive thermal storages. Active strategies for energy-intelligent buildings with advanced energy management and smart controls mainly include smart appliances, smart HVAC controls and flexible demand-side management.

4) Renewable system planning for replacement of traditional fossil fuel-based power plant is one of most powerful carbon elimination strategies to achieve the carbon-peak and carbon-neutrality targets. The increase in PV capacity to 455–605 GW will lead to the reduction of GHG emissions by 55% in 2030. For the clean power supply of district energy community, renewable systems mainly include onsite BIPVs, floating PV farms and onshore/offshore wind turbines.

5) Advanced energy conversion and management strategies can pave path for the carbon-neutrality transition, including power-to-X energy conversions (e.g., power-to-heat, power-to-gas and power-to-grid) and energy storage-based controls (e.g., floating setpoint temperature for thermal storage, state-of-charge based smart battery charging/discharging). Synergistic operation on multi-energy networks (e.g., cooling, heating and power grids, carbon and hydrogen networks) can improve the power complementary, power supply reliability, system decarbonization, and carbon-neutrality transition. Furthermore, interactive energy sharing with mobile energy storage can overcome the spatiotemporal intermittence of renewable power supply and exploit abundant solar-wind resources for spatial energy transfer.

6) Roadmap for 2060 carbon neutrality transition in China requires pilot initiatives and policy actions in building, transportation and industry sectors, respectively. In the building sector, compared with the benchmark scenario, carbon reduction potentials are 330 million tCO_2 (22%) via building energy saving, 299 million tCO_2 (20%) via renewable energy supply, 450 million tCO_2 (30%) via building electrification and power sector decarbonization, 420 million tCO_2 (28%) via carbon capture, utilization and storage technology. In respect to the entire energy chain in China, the past several Five-Year Plans from the 10^{th} in 2005 to the 14^{th} in 2025 aim to reduce the energy intensity and carbon intensity by around 65%. In the 2060 carbon neutrality scenario, ideal energy structure is assumed to be: 15% natural gas, 25% unclear energy, 20% biomass, 20% wind turbine, 15% solar PVs, and 5% others (like waste-to-energy). Decarbonization potentials for negative-emission strategies (like CCUS), renewable energy supply and energy-saving technologies are 3.85, 3.03 and 4.0 Gt CO_2 in the 2060 carbon neutrality transition framework.

The carbon-neutrality transition pathway is full of challenges, and joint efforts from different sectors and concrete support are necessary from district designers, energy planners, decision makers and so on. Outlook and recommendations include electrification and hydrogenation for multi-energy systems, energy-efficient and energy flexible buildings, carbon offsetting strategies (such as carbon capture and storage,[237-239] photosynthesis for conversion from CO_2 to organic compound), together with clear clarification on energy boundary for carbon neutrality transition.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

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